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Energy from sugarcane bagasse in Brazil: An assessment of the productivity and cost of different technological routes

Guilherme A. Dantas [a,*], Luiz F.L. Legey [a], Antonella Mazzone [b]

[a] Energy Planning Programe, Universidade Federal do Rio de Janeiro, 21945-970 Rio de Janeiro, RJ, Brazil
[b] Brazilian Studies Research, King's College London, King's Brazil Institute, Norfolk Building, Strand London, London WC2R 2LS, UK

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ABSTRACT

Bagasse from sugarcane is traditionally used in the Brazilian sugar and ethanol industry to meet the energy needs of its own production processes and, more recently, to generate surplus electricity for sale on the national grid. Currently, the industry faces a difficult choice between either enhancing electricity generation or increasing ethanol production through the biochemical processing of bagasse. The aim of this paper is to examine the most promising technical configurations for bioenergy production using sugarcane bagasse and to discuss which configuration would be the most attractive investment option for the industry. At present, electricity generation through Rankine cycle power plants is the only commercially available alternative. Nevertheless, the analysis cannot be restricted only to the short term. For this purpose, cost analysis for 2030 were developed, and even in scenarios where there is an effective cost reduction of untradeable routes, the alternative of burning bagasse to generate electricity provides the most benefits from an investor perspective.

Contents

1. Introduction

Twenty-first century policy makers in the energy sector face an increasing challenge to supply an ever-increasing demand while simultaneously mitigating the environmental impacts arising from energy production and use. One possibility for meeting this challenge is the widespread use of cleaner energy sources. Among these sources, bioenergy stands out as a relevant substitute for fossil fuels and a workable option for the mitigation of greenhouse gas emissions [1–3].

The transportation sector is a large consumer of energy, as it is responsible for 27% of worldwide demand and meets its needs primarily with petroleum derivatives [4]. As is well known, the widespread use of fossil fuels poses several problems, in terms of both environmental impacts, especially those caused by CO_2 and other harmful emissions, and sustainability. Thus, a sensible energy policy must include a proposal for innovative ways to handle the energy needs of the transportation sector. One candidate policy is the incentivisation of the use of biofuels [5], which have a lower environmental impact than fossil fuels and can be used by both Otto and Diesel cycle engines [6].

Ethanol appears to be a particularly useful biofuel because it can be used as either a substitute fuel (hydrous alcohol) or an additive to gasoline (anhydrous alcohol). However, it is important

* Corresponding author. Tel.: +55 2185282698; fax: +55 2125628777.
E-mail address: guilhermecrvg@yahoo.com.br (G.A. Dantas).

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to note that ethanol productivity varies according to the raw material used as an input. Corn starch ethanol has a productivity of 4000 l per hectare, significantly less than the 6800 lper hectare productivity of Brazilian sugarcane ethanol [7]. In addition, if plant starch ethanol is consumed at the large scale required by the transportation sector, large amounts of agricultural land would be required, causing an impact on food chain prices that may prevent the implementation of this alternative [8].

Cellulosic ethanol opens up a new possibility for ethanol production on a sustainable basis because its inputs can be composed of residual farm crops and forest waste biomass [5,9]. Despite the potential benefits, however, processing configurations for this technological route are still in the early stages of development and are not yet commercially competitive [8]. One of the obstacles for the dissemination of cellulosic ethanol is the logistics of supplying good quality biomass, which must conform to specific physical properties to ensure efficient and cost-effective production processes [10]. Bagasse is a fibrous residue from the sugarcane processing to extract the juice that is used in the production of ethanol and sugar. Sugarcane bagasse is widely available in Brazilian sugarcane processing mills [11]. Not considering the opportunity cost related to its use as a fuel in the generation of electricity as fuel for thermo plants, its only cost is storage [12].

Bagasse is traditionally used in the Brazilian sugarcane industry as a fuel for combined heat and power (CHP) systems implemented to meet energy needs of the mills [13]. In the past, the efficiency of systems using bagasse as fuel was lower than that of commercial power plants, because there was no incentive for efficiency, as regulations at the time did not allow for the sale of surplus electricity to the general public [14,15]. This situation changed with the reform of the Brazilian Electricity Sector [16,17], which created the necessary conditions for the commercialisation of surplus electricity in the national grid. Presently, all new mill projects (or expansions of older projects) include investments in cogeneration plants to generate surplus electricity [18,19].

The adoption of measures to reduce energy consumption in the in the mills' production processes associated with more efficient cogeneration technologies allows for the generation of a greater amount of bioenergy from bagasse, which can then be commercialized [20]. Of course, the amount of energy available for commercialization depends on the technology adopted. The technological landscape ranges from the simple combustion of bagasse, to ethanol production by lignignocellulosic hydrolysis or biomass gasification [7,21,22]. In the recent past, several studies have presented technical and economic analyses of different technologies as well as the comparative performances of ethanol production and biomass power generation [23,24]. In terms of biomass residues from sugarcane, [15,25] analyse different alternatives that can be used for bioenergy production. However, there is still a lack of specific data on bioenergy production from sugarcane waste [12].

This paper attempts to contribute to the field by presenting productivity figures on power generation and biochemical ethanol production processes based on sugarcane bagasse technical data. Additionally, the paper presents an assessment of the costs of each technology. Because of the lack of data regarding experimental processes and the fact that the vast majority of the new technologies are not yet commercially available, the data presented here are not exclusive to Brazilian industry[1] . Furthermore, plant costs include projects, installations and process contingencies, known as overnight costs, and differ from the total investment value because they do not consider the time value of money and start-up costs [26]. All monetary values are presented in 2010 dollars[2] .

Costs and productivity data refer to a mill producing only ethanol, with a processing capacity of three million tonnes of sugarcane per year. Further characteristics of the mill are as follows: (i) ethanol is produced during the harvest period only, and (ii) the mill operates for 200 days a year[3] using bagasse with 50% moisture, either as the only fuel for electricity generation or as the single raw material for cellulosic ethanol production.

The paper is organised into four sections (besides this introduction and the conclusion). Section 2 provides an overview of the main features of the Brazilian sugarcane industry. Section 3 examines the technological routes for electricity generation and their respective productivities and costs. Section 4 discusses the ethanol production from cellulosic materials, and provides an estimation of productivity and costs of these route. Section 5 compares the productivities and costs of different technological routes and discusses which represents the best investment option.

2. The Brazilian sugarcane industry

Since colonial times, sugarcane has been one of the most important agricultural products in Brazil. Sugar, and more recently ethanol production, has played an important role in the Brazilian economy [27]. In terms of the national energy matrix, sugarcane products are the second most used primary energy source [28]. This position is due to the large-scale use of ethanol as a fuel in the Brazilian light vehicle fleet, where it is either blended with gasoline as anhydrous ethanol in percentages ranging from 20 to 25% or used as hydrated ethanol. The consumption of the latter has been increasing with the arrival of flex-fuel cars, whose engines can use both hydrated ethanol and gasoline in any proportion [7].

Approximately 98% of the energy needs of sugarcane processing mills are provided by the burning of bagasse [29] in cogeneration plants [30], which deliver the thermal, mechanical and electric types of energy required in the production of ethanol and sugar. The energy used by the Brazilian sugar and ethanol industry is based on the Rankine cycle engine, which is a heat engine with a vapour power cycle [15]. The working fluid is water, and through the direct burning of fuel, it produces the steam used to create mechanical energy [31,32]. The Rankine cycle has a low level of energy efficiency but has the advantage of accepting many different types of fuels, including those with lower caloric value, such as sugarcane bagasse. The amount of mechanical energy created in a Rankine cycle engine depends on steam expansion in the coupled turbine. Thus, if greater-pressure boilers are used, larger amounts of mechanical energy can be obtained. In terms of the Brazilian sugarcane industry, the use of 100-bar or even 67-bar boilers, rather than the historically used 21-bar boilers, can catapult a mill from being an energy self-supplier to being a supplier of surplus electricity [18,33].

In the past, the use of bagasse had a low efficiency due to the regulatory framework of the electricity sector, which did not allow for the sale of surplus electricity. The purpose was to maximise the amount of bagasse burned, as it was difficult not only to store it, but also to sell it as a commodity [14].

[1] Only the electricity production in Rankine cycle plants is commercially available in Brazilian industry. The cost data from other international routes are approximations, as are FOB data.

[2] Values in 2010 US dollars were obtained using the GDP deflator from World Bank data.

[3] Based on the supposition that the productive unit will be integrated with the conventional ethanol plant operating during the crop period. This option focuses on the prospect of economy of scale and reduces logistical expenses.

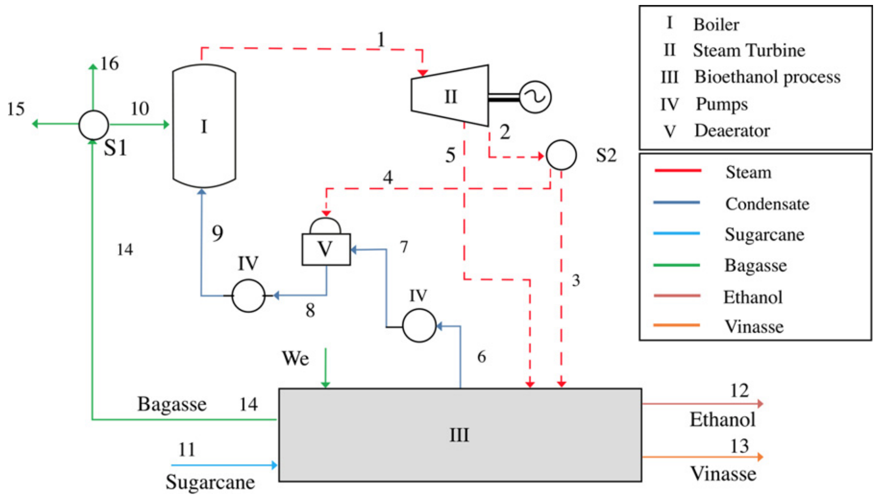

Fig. 1. Cogeneration system based on Rankine cycle: backpressure steam turbines. *Source*: Dias et al. [20].

Consequently, mills opted for plants with low temperature and pressure (21 bar and 350 °C) and backpressure turbines [20]. A typical configuration of a plant traditionally used in the industry is illustrated in Fig. 1.

Thus, despite the importance of sugarcane biomass among energy sources in Brazil, its full potential is far from being realised, as much of it is wasted. Of the total amount of energy present in one tonne of sugarcane[4], only the one third contained in the sucrose is used for ethanol production. From the remaining two thirds, only the bagasse is partially used for electricity generation, while the remaining portion present in the sugarcane straw is mostly wasted [7]. The prospects of an increased demand for sugar over the next few years, along with a significant growth in the demand for ethanol, imply the need for a proportional expansion in sugarcane harvesting and crushing. Thus, it is possible to envision a crop of 1038 million tonnes of sugarcane by 2021, nearly twice the 569 million tonnes of the 2008/2009 harvests [34]. For each tonne of processed sugarcane, there are 270 kg of bagasse [29], resulting in a significant amount of bagasse available for energy use in the coming years.

Therefore, it is appropriate to adopt more efficient technologies provided, of course that they are economically viable. After the changes in the regulation of the electricity market that allowed for the selling of bioelectricity to the grid, cogeneration plants were built with Rankine cycle configurations that provided a higher level of efficiency, thus providing a new source of income to the sugarcane industry [15]. Nevertheless, an even more efficient use of sugarcane bagasse would arise from the adoption of advanced technological routes[5], such as electricity generation from bagasse gasification or through the ethanol produced by the hydrolysis of lignocellulosic material. The following sections analyse the productivities and costs of the different technological routes for electricity generation and ethanol production to allow for comparisons between the performances of the available options.

[4] One tonne of sugarcane contains 7200 MJ [7].

[5] The term "technological route" is used here as synonymous to the expression "technological trajectory" defined by Dosi [35] as "the direction of advance within a technological paradigm", which in turn are "a set of procedures, a definition of the 'relevant' problems and of the specific knowledge related to their solution." (*ibid.*)

3. Technological routes for electricity generation using sugarcane bagasse

This section describes the two main technologies that can be employed for electricity generation through the use of biomass. The first is based on the traditional Rankine cycle, and the second employs the more sophisticated combined cycle turbines.

3.1. Rankine cycle based electricity generation

The simplest way to increase the efficiency of bagasse utilization is adopting Rankine cycle plants configured to maximize the generation of surplus electricity [25]. This is possible through the introduction of boilers with higher temperature and pressure and the substitution of backpressure by condensing-extraction turbines [18,20]. As a matter of fact, these measures represent a progress along an existing technological trajectory [35].

A condenser in the turbine's exhaust allows for greater flexibility, and in conjunction with the pre-heated water fed into the boiler, it significantly increases the overall efficiency of the cogeneration plant. The use of a condenser maximises electricity generation because the steam can be expanded to the minimum pressure obtained in the condenser. The flexibility brought by the condenser allows the mill to operate during the crop off-season, in contrast to mills that employ backpressure turbines. In the latter case, the demand for heat in the production process of sugar and ethanol affects the production of steam in the boiler, as this heat is extracted somewhere in the middle of the expansion process through backpressure turbines. The independence of the steam condensation and the production process of ethanol and sugar permit the adoption of efficiency measures in the electricity generation process [29]. Fig. 2 shows the basic configuration of this technology.

In this study, we consider a cogeneration mill that employs high-technology extraction and condensation systems. The term "high technology" refers to processes employing high-pressure boilers with combustion chambers, where the biomass is burnt in suspension, efficient turbines, and a series of heat exchangers, including heaters, super-heaters and reheaters. In addition, we assume that the cogeneration system adopts measures to reduce the consumption of steam, such as the use of electric instead of

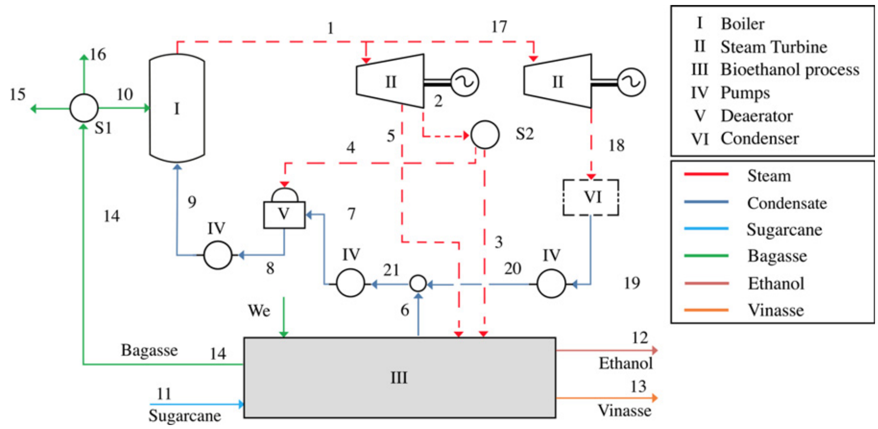

Fig. 2. Flowchart cycle condensing-extraction to generate maximum electricity. *Source*: Dias et al. [20].

mechanical drives. The specific technical parameters adopted are as follows [36]:

- Boilers of 100 bar at 530 °C
- Steam processed at 25 bar
- Specific consumption of steam: 400 kg per one tonne of cane

With these parameters, it is possible to obtain a surplus generation of approximately 86 kW h of electricity per tonne of sugarcane processed. The investment cost was estimated at US $1400 per installed kW, and operation and maintenance costs were estimated at US $84.00 per installed kW per year [36]. It should be noted that future cost reductions of such a system are unlikely because it involves a mature technology.

3.2. Electricity generation with combined cycle turbines

Bioelectricity generation from direct biomass combustion in Rankine cycle engines has an efficiency bound of 25% [37,38]; in contrast, gas turbine generation can achieve higher efficiency levels [39,40]. To take advantage of this efficiency, however, biomass gasification is necessary[6] .

The biomass gasification process consists of thermochemical procedures that do not present relevant difficulties. However, there are problems in dealing with any sort of available fuel, such as reliably and safely maintaining the quality of gas produced. The biomass gasification process has four distinct physical chemical stages: drying, pyrolysis, reduction and combustion. Each stage occurs in a separate portion of the gasifier, and their sequence is a function of project characteristics. A gasifier must produce high-quality clean fuel gas from a wide variety of inputs in a manner that is both efficient and economical. As these goals are conflicting, the choice of the gasifier should depend on the available fuel and its eventual use [41].

While coal gasification typically occurs in entrained flow gasifiers, it is not clear which technology is the most appropriate for biomass [42]. Fixed bed gasifiers present technical limitations concerning the required size of the biomass pellet and the considerable amount of TAR produced. Although fluidised bed gasifiers have suitable characteristics for biomass gasification, they are not yet widespread technology, even for the processing of more traditional raw materials, such as coal and petroleum residues.

Entrained flow gasifiers use pulverised fuel particles that react with gasification agent at high speed in a co-current flow. This system represents the alternative with the highest demand on fuel homogeneity. However, the technology works with a wide range of fuels and produces high-quality gas. These facts explain why entrained flow gasifiers generate approximately 70% of the syngas produced today [26].

Another advantage of the entrained flow gasifier is its short reaction time, which allows for large-scale processing. The gasifier requires biomass pulverisation to perform its high-speed reaction and biomass moisture reduction for upstream pyrolysis; thus, there is a significant oxygen diminution in the syngas. These operations represent a large and costly technical effort [43]. Nevertheless, the entrained flow gasifier can operate at different scales, and it represents the most promising commercially available technology for biomass gasification [44].

After being cleaned, the syngas can be injected into the gas turbine combustion chamber in a system called biomass integrated gasification–gas turbine (BIG/GT) [29]. Some measures can be adopted in BIG/GT to increase thermoelectric cycle efficiency. Steam injection increases the available power of the turbine[7] [45–47], while intermediate cooling increases the available power by reducing the air specific volume and thus the power required to compress the air [48].

The biomass integrated gasification–gas turbine combined cycle (BIG/GTCC) system is a BIG/GT system derivation that provides higher-efficiency results. A combined cycle power plant consists of coupled steam and gas turbines. This system uses the heat of the gases from the gas turbine exhaust to generate steam, which is then used as a working fluid in a steam turbine [49]. As this technology has the highest thermoelectric performance, this paper will adopt a combined cycle plant as the technological paradigm for electricity generation from sugarcane biomass gas [50,51].

Due to the physical and geometrical characteristics of sugarcane bagasse, the entrained flow gasifier is useful for minimising possible incompatibilities with the gas turbine, as this process adopts the oxygen to a high calorific gas value. Of the methods currently adopted for biomass conversion into gas, we assume that pressurised gasification is justified by the subsequent use of the gas in a medium-scale combined cycle plant [52]. To generate electricity, the gas is used in a combined cycle plant with steam injection and intermediate cooling [29], as shown in simplified

[6] The synthesis gas produced from the gasification of biomass can be used not only as an input to electricity generation but to the production of synthetic fuels as well [5,8].

[7] These gains are possible because steam injection increases the mass flow and specific heat of the working fluid entering the turbine. The injection of steam also reduces NO_x emissions [47];

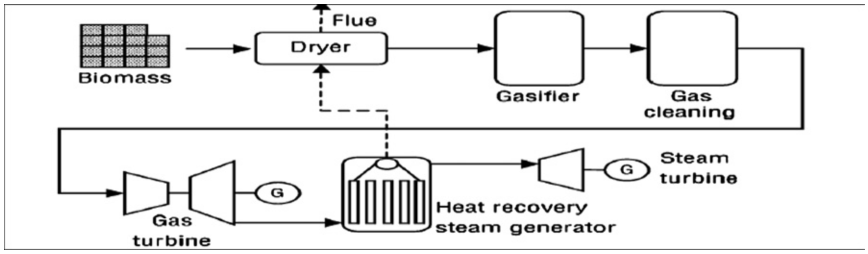

Fig. 3. Flowchart BIG/GTCC plant. *Source*: Larson et al. [51].

form in Fig. 3. We suppose that energy demand required for ethanol production will continue to be served by extra-condensing turbines; in this sense, only the remaining bagasse is gasified [25]. Thus, the plant is considered to have 567,000 t of bagasse available[8].

BIG/GTCC productivity is based on the bagasse conversion to biosyngas and the combined cycle plant performance. The assumption is that the gasifier will produce 300 kg of biosyngas H_2/CO with a molar fraction equal to 2 for every 1100 kg of bagasse processed at 50% moisture. The syngas has a lower calorific value of 23.9 MJ/kg gas [52]. When used in a combined cycle plant with an efficiency rate of 45% [53], sugarcane generates approximately 155 kW h excess per tonne of cane processed. Thus, it is possible to obtain a productivity rate that is 80% higher than what was presented in the previous subsection for steam cycles.

BIG/GTCC technology is not yet available on a commercial scale, especially for sugarcane bagasse applications, and there remains considerable uncertainty about its costs. To provide the estimated expense of this route, this paper reports data from the international literature regarding the costs of biomass gasification in entrained flow gasifiers and a combined cycle plant. Based on these data, a gasification plant with a capacity of 4000 MW input is estimated to cost US $1178 million [44]. In turn, the investment cost of a combined cycle plant is US $785 per installed kW [54,55].

However, production costs are sensitive to scale, and the previous cost data are not compatible with the scale of the reference plant used in this paper. In cases where there is a lack of cost information, it is common to use the logarithmic-type relationship Cost X=Cost Y (capacity X/capacity Y)^N, where N is a scale factor with a value between 0 and 1, with lower values of N for higher scales. The N value used for biomass electricity generation technology is 0.7 for BIG/GTCC [54]. Therefore, the cost of a BIG/GTCC system compatible with the plant characteristics considered in this paper can be estimated at US $3600. Regarding operational and maintenance costs, generating electricity with a gasified biomass plant has a 4% investment annual cost [25], equalling US $144 per kW installed.

4. Production of ethanol from cellulosic material

The main components of plant matter are not sugar and starch but cellulose, hemicellulose and lignin[9] [56]. Among these components, cellulose and hemicellulose can be converted into ethanol via biochemical processes[10] , which are more complex and more energy intensive than ethanol production from starch or saccharides [6]. The crystalline structure of cellulose complicates hydrolysis, and the associated lignin-cellulose-hemicellulose complex forms a physical barrier that prevents access to the microbiological process [57].

Ethanol production from lignocellulosic biomass requires the separation of its fractions through pre-treatment methods. Pre-treatment breaks down the lignin protection and the crystalline cellulose structure creating the conditions for hydrolysis of polysaccharides [58]. Different types of pre-treatment exist based on different biological, physical, chemical and combined methods [59].

For each type of biomass feedstock, there exists a specific pre-treatment technique that improves its hydrolysis and subsequent fermentation. Thus, it is fundamentally important to define the advantages and disadvantages of existing pre-treatment systems as they relate to biomass characteristics. Furthermore, the investment cost, operating costs and availability of expertise for each pre-treatment are additional variables that must be considered in the selection process [8,60]. In the specific case of sugarcane bagasse, pre-treatment with dilute acid is the mostly used [11,61].

As soon as the pre-treatment process has been conducted, hydrolysis takes place. This step converts cellulose and hemicelluose[11] into glucose and xylose through a catalytic reaction in which the agent can be a diluted acid, a concentrated acid or an enzyme. Without this pre-treatment, the hydrolysis yield is less than 20%, in contrast with the 90% yield achieved using pre-treatment [59]. The acid hydrolysis process is efficient and relatively competitive, despite its associated pollutants and waste products that inhibit subsequent fermentation [57]. In contrast, enzymatic hydrolysis is less toxic and can yield up to 95%, versus the 75–85% yield of acid hydrolysis [25]. This process can be enhanced by simultaneous saccharification fermentation (SSF), which minimises enzyme inhibition by accumulating sugars to achieve high cellulose conversion yields [62]. Therefore, it seems plausible to say that enzymatic hydrolysis is the mostly promising route [8,11].

The commercial viability of cellulosic ethanol requires the development of an efficient production method that includes the fermentation of all sugars from pre-treatment and hydrolysis. The fermentation of hexoses into ethanol is a mature and well-mastered process accomplished by yeast or bacteria. However, most processes do not ferment pentoses because the yeasts

[8] One tonne of cane sugar has 270 kg of bagasse at 50% moisture. Therefore, the standard plant used in this article has 810,000 t of bagasse. Considering that 30% of this amount is intended for the self-supply energy demands of the conventional ethanol production process, the amount of bagasse to be gasified is 567,000 t.

[9] Lignin can be used for energy generation to satisfy the needs of the process and the production of other chemicals.

[10] Cellulose is a linear rigid polymer that can be converted, with difficulty, into glucose, a six-carbon sugar with a well-known and widespread fermentation technique. In contrast, hemicellulose is easily hydrolysed, but the xylose originating from its hydrolysis cannot be fermented easily.

(*footnote continued*)

[11] In the pre-treatment with acid, hemicellulose hydrolysis takes place during this phase. On the other hand, physical pre-treatment hydrolyses hemicellulose only partially. In this latter case, when the hydrolysis is acid, there will occur furfural formation because cellulose hydrolysis conditions are more severe than those applied to the hydrolysis of hemicellulose.

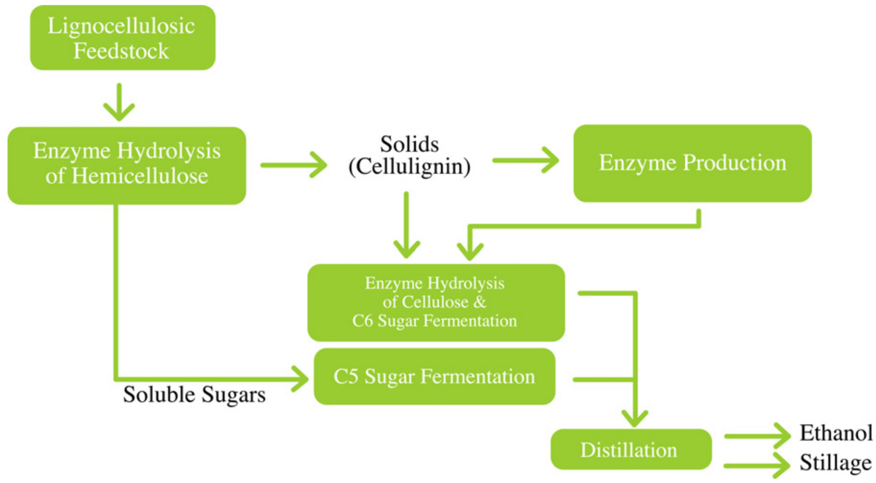

Fig. 4. Flowchart SSF process. *Source*: Pereira [65].

commonly used to ferment glucose cannot metabolise xylose [63].

Great efforts are being made to develop metabolic pathways capable of fermenting both pentoses and hexoses with satisfactory yields, an expansion of the SSF into simultaneous saccharification and co-fermentation (SSCF) [59]. However, the commercial availability of this process depends on recombinant microorganisms and their compliance with bio-security standards.

The cellulosic ethanol production plant proposed by this paper operates using pre-treatment with diluted acid, hydrolysis by enzymes and the SSF process, and is illustrated in Fig. 4. At the laboratory level, approximately 162 l of ethanol can be obtained per tonne of bagasse processed, 55% of which derives from the cellulose fraction and the remainder from the hemicellulose fraction [64].

The hypothesis is that 30% of available bagasse is necessary to meet the energy demands of the conventional ethanol production process. Regarding the production of cellulosic ethanol through the biochemical pathway, the amount of available lignin is insufficient to meet the energy demands of the plant[12] . Thus, part of the bagasse will be exploited by the self-supply power plant. The amount of bagasse used for ethanol production is assumed to be 375,000 t, and the productivity of this route is estimated at approximately 20 l of ethanol per tonne of cane.

The investment cost of an SSF plant using diluted acid pre-treatment is approximately US $340 million. This estimate is based on a plant that processes 2000 t of dry biomass daily, the equivalent to 2666 t of biomass at 25% moisture over 350 days per year [66]. The plant proposed in this paper instead processes, three million tonnes of cane per harvest and 375,000 t of bagasse over 200 days per year. Consequently, there are diseconomies of scale associated with the decreased production scale. Therefore, we use the exponential method, with N equal to 0.7, to make an adjustment for scale. The investment cost of a cellulosic ethanol plant using the biochemical process is estimated at US $266 million. Regarding variable costs, it is necessary to highlight the role of enzymes. Currently, the enzymes used in these plants cost approximately US $0.69 per gallon of ethanol produced, and the total variable cost is approximately US $1.63 per gallon of ethanol [66].

[12] 95 t of lignin and 27 t of cellulose are recovered per 1000 t of bagasse (wet basis) processed. The use of these by-products allows for the reduction of energy consumption from 39.93 MJ per litre of ethanol to 23.52 MJ. It should be noted that the use of other residues, such as enzymes and yeasts, could further reduce the power consumption of the process [64].

5. Comparative analysis of technological routes

A central concern of the so-called rational economic agent is the return of an investment expressed in terms of the maximisation of the financial return on invested capital. Accordingly, the comparative analysis of alternative investment opportunities is based on indicators, such as internal rate of return (IRR) or net present value (NPV) [67], which inform about the attractiveness of each alternative. The indicator selected for the present analysis was the equivalent annual cost (EAC), because it considers annuity factors in its definition, thus allowing for comparisons among annualised costs of projects with different lifespans [68]. Since the NPV computes the present value of all future cash flows it loses information about the project lifespan. In its turn, the IRR is adequate to cash flows that present positive as well as negative values, which is not the case here, where only cost data is available. The EAC can be computed through the following equation:

$$Equivalent\ Annual\ Cost = \frac{NPV}{1/r - 1/r(1+r)^t} \quad (1)$$

where r and t are the discount rate and the project's lifespan, respectively.

The choice of the most appropriate discount rate is essential for a correct comparative analysis between projects with different technologies, especially in the energy sector, where project lifespans tend to be large [69]. As we emphasise the investor's perspective in this paper, a rate based on the opportunity cost of capital (OCC) will be adopted. This rate can be calculated through the weighted average cost capital (WACC), which considers the debt and equity rates in proportion to their participation as financing sources and the income tax rate [13] [67]. We will assume that the discount rate is the same for all technological routes, despite their presently different levels of maturity, for the following reasons:

i. To account for the uncertainties related to different technological routes, it is more appropriate to build alternative future scenarios than to rely on different discount rates [68].
ii. The Brazilian Development Bank (BNDES), which is the main moneylender of capital-intensive projects in Brazil, does not

[13] In Brazil the business income tax rate is 34% [70].

make any distinction for the financing conditions of projects concerning distinct renewable energy sources [71].

Additional assumptions for computing the OCC are as follows:

i. Capital structure of projects: 30% of equity and 70% of debt
ii. Debt rate (as financed by BNDES): 9%[14]
iii. Private capital costs: 12% for bioelectricity projects and 16% for ethanol[15]

Therefore, the WACC (and thus the discount rate) for bioelectricity generation is 7.76%, while it is 8.96% for ethanol production. It is assumed that both Rankine cycle plants and BIG–GTCC plants have a lifespan of 25 years [29]. A lifespan of 20 years is assumed for technological route for ethanol production [66].

Using the parameters and cost data above[16], the overall EAC can be calculated, as well as the EAC per unit of energy, which is an indicator of the productivity of the different technologies studied. Because electricity and ethanol are traded in distinct markets, the EAC must be adjusted for these market distinctions to make valid comparisons. This adjustment was made through the use of the relative prices of one unit of energy in the form of ethanol and one unit of energy in the form of electricity. The adopted relative price of ethanol to electricity was 1.46[17] . Table 1 shows the EAC, the EAC per unit of energy and the adjusted EAC per unit of energy[18] .

From Table 1, it can be seen that ethanol production costs are higher than those for generating electricity. This finding corroborates the result found by Wright and Brown [74] regarding the lack of competitiveness of the ethanol produced from lignocellulosic material. Thus, the allocation of bagasse to electricity generation constitutes a more attractive investment option. Furthermore, the figures shown in Table 1 indicate that from an investment point of view, Rankine cycle plants perform better than BIG–GTCC systems. There is an additional economic barrier to BIG–GTCC technology, as it is not yet commercially available to the Brazilian sugarcane industry. This fact explains why current investments are directed towards Rankine cycle plants [15].

For a more complete analysis, however, we must examine the future costs of the technologies presented in Table 1, i.e., how they may evolve over time. This consideration is even more important if we observe that present technologies, with the exception of Rankine cycle plants, are still in the early stages of development. In other words, we must analyse the competitiveness of these technologies in the long run, after economies of scale and improved techniques have been incorporated. This estimation is not an easy task, as the relative competitiveness of different technological routes will vary along time to different degrees.

Table 1
Costs and competitiveness of technological routes.

Technological route	EAC (millions US$)	EAC per unit of energy (US$/GJ)	Adjusted EAC per unit of energy (US$/GJ)
Electricity—Rankine cycle	12.534	13.51	19.72
Electricity—BIG–GTCC	43.242	25.85	37.74
Ethanol—Biochemical route	44.433	34.70	34.70

Table 2
Adjusted EAC per unit of energy (US$/GJ) for the different scenarios in 2030.

Technological route	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Electricity—Rankine cycle	19.72	19.72	19.72	19.72
Electricity—BIG–GTC	37.74	30.52	37.74	30.52
Ethanol—Biochemical route	34.70	34.70	24.29	24.29

There are difficulties regarding the estimation of experience curves for each of the technologies studied[19] , given the uncertainties involved. Consequently, the examination of the relative competitiveness of the technologies in 2030 will be performed by the methodology of scenario analysis. This methodology is useful when the uncertainties involved are difficult to quantify and a prognosis based on extrapolation from the past is not meaningful. In fact, scenario analysis attempts to identify possible behaviours of variables in a "if then" context [76,77].

The hypotheses for the cost reduction projections are as follows:

i. Electricity generation through Rankine cycle plants uses a mature technology. Therefore, productivity gains should be marginal and cost reductions unlikely.
ii. The Brazilian capital goods industry should be able to provide all of the equipment needed for any of the technological routes studied. Therefore, shipping costs will not affect the relative competitiveness of the different routes.

The scenarios analysed were as follows:

- Scenario 1: There will be no significant cost changes in the time period considered for any of the technologies. In other words, the data in Table 1 remain approximately unchanged until 2030.
- Scenario 2: There will be a 20% cost reduction in the BIG–GTCC route [78]. The remaining routes maintain their respective costs.
- Scenario 3: There will be a 30% cost reduction in the biochemical route [8]. The other alternatives maintain their respective costs.
- Scenario 4: The cost reductions of scenarios 2 and 3 are considered simultaneously. Only the Rankin cycle route for electricity generation maintains its costs.

Table 2 summarises the obtained results, showing the adjusted EAC per unit of energy for each technology under the different scenarios studied.

It is evident from Table 2 that even with significant cost reductions in emerging technologies, electricity generation through Rankine cycle plants remains the most competitive

[14] This number was calculated as the sum of the long-term interest rate (6% in May 2012), the basic remuneration of 0.9% from BNDES, the financial intermediating rate of 0.5% and the credit risk rate of 1.6%.

[15] This distinction stems from the greater risk of the ethanol market. In particular, it arises because of the Brazilian electricity regulatory framework, which allows for bioelectricity trading in auctions with a guaranteed sell price.

[16] In addition, estimates for electricity generation accounted for a cost of US $5 million related to the grid connection [15]; charges for the use of transmission lines (U.S. $ 4.93/a month per kw) [72]; and an inspection fee charged by the regulatory agency (ANEEL) (U.S. $ 1.08 a year per kw [73].

[17] This value was estimated through the average price of Brazilian anhydrous ethanol between January 2006 and June 2011, US $570/$m^3$ (data obtained from the Centre for Advanced Studies in Applied Economics of the University of São Paulo—USP), and the average price of bioelectric power resulting from auctions in 2010 and 2011, US $63.00/MW h (price without taxes).

[18] Taxes over the plant lifespan are not included.

[19] The extrapolation of the experience curve from other technologies faces enormous difficulties due to the assumptions necessary to carry out projected costs [75].

Table 3
Cost reductions necessary for the competitiveness of emerging technologies.

Technological route	Reduction (%)
Electricity—BIG–GTCC	48
Ethanol—Biochemical route	43

alternative for energy production from sugarcane bagasse. Performing a sensitivity analysis to the discount rate and the relative price of ethanol to electricity, in the range −15% to +15% of the base values, indicate that the burning bagasse for electricity generation remains the most attractive option in all scenarios. The figures in Table 3 show the cost reductions necessary to make the emerging technologies as attractive as conventional bagasse burning plants.

From Table 3, we can see that if a dramatic reduction in the costs of alternative technologies does not occur, investments in sugarcane bagasse energy production will be directed to electricity generation through Rankine cycle plants, even in the middle and long terms.

However, it is necessary to emphasise that these projections only consider the investor's perspective. From the social point of view, the benefits and costs of each process may involve other variables. For example, routes with lower energy productivity may not be desirable, even if they are less costly. These considerations are beyond the scope of the present paper, but they remain extremely important for the delineation of short- and medium-term policies concerning the most appropriate investments for energy production [69].

6. Conclusions

Despite its place as the second main source of energy in Brazil, sugarcane is still not fully exploited as an energy crop. Sugarcane may provide a part of the solution to the global challenge of expanding energy supplies in a sustainable manner. One of the reasons for the inefficient use of bagasse as fuel in large-scale ethanol plants is that it is cheaper than other alternatives. Although the production of cellulosic ethanol in Brazil tends to be more competitive than in other countries, the current use of the bagasse is to provide energy for the plant itself and to generate surplus electricity for sale on the market.

This paper provided a comparison between the productivities and available cost data for different technological routes to direct future investments into more promising and profitable options. The data indicate that electricity generation from biomass combustion is the only economically feasible option at present. However, except for electric power generation based on the Rankine cycle, these technological routes are still in the early stages of development and are not yet commercially available. Therefore, there is a high level of uncertainty about their future possibilities. The analysis cannot be restricted to the short term, as many infant technologies become competitive in the medium and long term.

To analyse possible developments over a longer time scale, cost projections based on scenarios for 2030 were constructed. Even at this point, however, burning bagasse to generate electricity remains the best option from an investor perspective.

Nevertheless, the costs and benefits of different technological routes can vary based on social perspective. This work is relevant to short- and medium-term political and economic development strategies, as well as to the design of appropriate incentives for encouraging the introduction of these routes to the market. It would be interesting to investigate how these different routes perform when the Brazilian energy sector is considered from a whole-society perspective.

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